SOME CONSIDERATIONS WHICH AFFECT THE MODELLING OF SEGMENTAL BLOCK PAVEMENTS FOR INDUSTRIAL APPLICATIONS

J M Clifford

C.ENG, M.I.C.E., M.I.H.T., M.S.A.I.C.E.

Summary

There is a need to provide input paramaters for computers aided design of segmental block pavements for abnormal loads in very heavy industrial load application. This paper reviews the numerous variables involved and suggests caution in using some data such as modulus of elasticity. A series of mathematical modelling and site testing with a Heavy Vehicle Simulator is reported. Results of these tests are discussed and an estimate of modulus for the block, bedding and jointing sand composite layer is given.

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1. PURPOSE OF MODELLING

Segmental block pavements are being used increasingly in industrial applications which is one of their greatest potential uses especially for heavy and very heavy industrial use where point loads for stacking and high wheel loads are encountered. Present soil mechanics and pavement engineering evaluation techniques are suitable for 'normal[1] load applications. The extension of the 'normal* ranges to the spectrum of loads common in industrial pavements requires a means of relating known parameters such as strain, effective and resilient modulus and stress distribution characteristics under 'normal* road pavement conditions, to those which occur in industrial loading.

2. METHOD OF MODELLING

Modelling of segmental pavements by a variety of methods permits rapid evaluation of changes in materials, layer thickness, density, moisture content and applied loads. Modelling can be done in several ways, e.g. mathematical model analysis and small-scale laboratory model studies. In order to use currently available modelling methods most effectively, for industrial block paving design, a combination of mathematical and laboratory methods was chosen. The National Institute for Transport and Road Research (NITRR) has a number of computer programs on file which have been developed for layered pavement analysis (e.g. MECDEI (1977)(1) and MECDE3 (1983)(2), CHEV4 (1977)(3), SLSYM5 (1983)(4) and others which relate to linear elastic layered theory, and FEPAVE (1983)(5) and MAPS (1983(6) which are based on non-linear finite element methods).

For physical modelling of segmental block pavements, a unique evaluation machine developed by the NITRR, known as the Heavy Vehicle Simulator (HVS), and its associated Instrumentation, were used.

This equipment measures the various soil parameters during trafficking equivalent to many years of use, so that comparisons with mathematical predictions can be made.

A combination of techniques permitted a study to be made of the effects of various applied loads, layer thickness and strengths, relative layer positions and different material types. Characterisation of the blocks, their joints and the bedding sand in in combination as a composite structural layer was also possible.

3. REQUIREMENTS OF MODELLING

Effective modelling requires the input of response parameters which have been either measured or predicted to a reasonable degree of accuracy from previous work. In order to include more accurate input data in the model, a rapid and effective evaluation technique was needed. Since many of the parameters were interdependent, single response modification and changes were possible at any stage of the analysis thereby producing a simple yet meaningful means of analysis.

4. PHILOSOPHY OF MODELLING

There are many aspects to modelling, especially where the highly complex characteristics of soil is concerned. In practice many assumptions must be made to reduce the number of variables and specific values for these variables must be chosen for input into mathematical models.

Results generated by model analysis techniques therefore, must be compared with those achieved from field tests and a process of reiteration of amended, specific input values may be necessary for realistic data. Since the importance of all the various parameters on the

total pavement performance is not as yet fully appreciated a rating to second or third order of importance of some of these parameters was considered necessary.

4.1 Limitations and assumptions of modelling

Soil as a structural medium is very much more variable than a material such as steel. The variability of apparently similar materials constructed to the same specification is significant. Variability is well known and can be ascribed inter alia to variable quantities of solids, fluids and gases within a soil matrix; variable angularity and size of individual solid soil particles; percentage of granular and cohesive components of the material, etc. Material variability results in different response modes under applied loading. The gradual dissipation of pore pressures within cohesive materials under statically applied loads causes consolidation in cohesive materials, whereas substantially resilient deformations are experienced under travelling loads. Repeated loading causes a variety of response modes within a soil matrix and causes visible differential settlement or rutting in an inadequately supported surfacing layer due to a combination of the above effects.

Material variability has always been a problem in mathematical evaluation methods. It has been catered for in a variety of ways such as the inclusion of various constants in mathematical formulas and the use of average or typical values of resilient or effective modulus. None of these methods is completely satisfactory, and even detailed evaluation to accuracies of several decimal places, which is, in many cases, possible in computer program analysis, is often not required and can be unnecessary or even misleading. These highly exacting analyses, which are based on assumptions and input values with large factors of safety do not necessarily indicate the optimal potential of the design. As a consequence, there is often a demand by specifiers for better materials than may actually be required in practice.

Assumptions concerning linear elastic response, homogeneity, isotopic behaviour and constant stress-strain relationships are made in mathematical evaluations. In many cases, overdesign occurs or errors in evaluation are made because little or no structural value is given to the subgrade. However, when a subgrade is considered, either its soaked Californian Bearing Ratio (CBR) is used, and in many cases such a condition is unlikely in large parts of Southern Africa for most of its life, or the subgrade is considered as a semi-infinite layer of assumed properties.

conditions surface loading, whether transitory or static, is likely to affect material to a depth of at least 3 m below the surface. The subgrade must therefore be a significant part of the design.

Since soils are highly complex, characterization of materials is not a simple exercise. Many assumptions clearly need to be made in modelling. Appreciation of these limitations is especially important for the optimization of designs at an acceptable degree of confidence. Modelling must then be seen only as a guide to optimization. Complete optimization must include a careful blend of theory and experience; moreover, both these aspects need to be qualified with a practical safety factor to account for material variability.

4.2 Other factors in modelling

There are several other factors in modelling segmental block pavements which must be considered in an optimum design. These include environmental factors, reflection of pulses generated by applied loads on relatively hard layers within structural supporting layers - the containing and screening effect of any fabrics, geotechnical materials used and the use -of open-graded materials which may provide an extremely elastic material of low density and high void ratio.

By definition environmental factors include not only climate but also the location of the material in relation to other materials surrounding it. Climatic effects are difficult to model realistically but their importance can be seen in sections of disused pavements which deteriorate in time even with no applied loading. Environmental factors that act on block pavements during the settling-in time can cause, for example, the development of a plug of detritus in the joints between the blocks, which would be difficult to simulate in modelling.

Stress dissipation in soils is a complex subject and can be influenced by: the moisture content, pockets of fairly dense buried material within a less dense layer and the cohesive and granular content of the soil matrix. In laboratory modelling, stress dissipation can be unrealistic due to the effects of moulds and other containing devices which are necessary for the tests.

4.3 Choice of modelling methods

The principal modelling techniques are: (i) mathematical models, including the use of computer programs specifically designed to analyse the input data

prepared to evaluate data from triaxlal and other repeated loading operations, where many variables such as climatic effects are eliminated; (iii) site evaluation and modelling of sections of actual pavement or evaluation of a limited sample section constructed under actual site conditions and where individual loads or repeated loading representing many years of use can be modelled. In addition, the response of individual layers, interfaces between layers and surface conditions can be measured to verify the modelling technique. The HVS system is an ideal tool for this type of site evaluation.

Because there are specific advantages of the various modelling techniques, a combination was considered the most effective way of modelling segmental block pavements. Modelling of the heavy industrial segmental block pavements by these means was therefore used to translate existing performance criteria for heavy and very heavy loading applications more readily. Initial modelling by mathematical analysis methods was made using linear elastic and finite element programs. The data generated by the mathematical model was then 'tried' by both laboratory and site modelling using actual applied loads and their associated responses within the structure until the modelling was acceptable to a high degree of confidence.

Considerable experience with load equivalency factors had already been established by HVS work which enabled the applied loads in the model to be rapidly increased to the very heavy loads experienced in industrial applications.

5. MECHANISTIC INPUT

The recent development of theoretical methods for the complex analysis of pavement structures by layers permitted the evaluation of the pavement as a total mechanism. This is known as mechanistic design, a term introduced by Paterson and Maree (1978)(7). The modelling technique allowed the stresses, strains and displacement at various points within a particular layer and at the layer interfaces to be computed. Mechanistic input data of the various criteria required for layers used in the heavy industrial designs are given in Figure 1.

6. STRESS DEPENDENCY

It is known that granular materials show stress-stiffening behaviour which is a function of the sum of the principal stresses and constants derived from laboratory regressions (Maree et al (1980))(8). Following a series of experiments, typical stress-dependent behaviour of a granular base was found and is shown in Figure 2. In the design of heavily and very heavily loaded segmental block pavements if the choice of base and subbase material is granular, improvements in carrying and support capacity with increased load can be expected.

7. EXAMPLE OF MATHEMATICAL MODELLING

Several designs from the South African catalogue of designs(9) were chosen for analysis. The industrial designs were considered the most demanding for modelling. A comparison of predicted behaviour with that measured with a Heavy Vehicle Simulator Tests enabled iteration of input values to fit the model.

Sections of pavement were constructed and Multi-depth deflectometers (MDD's) were installed in three locations. One location assumed that an HDD was directly under the centre of a single segmental block (longitudinally and latitudinally) and others were located at the edge of two adjacent blocks. (Figure 3). The HVS was used to apply trafficking to the pavements and throughout the tests various measurements were made and recorded.

8. RESULTS OF THE EXAMPLES OF MODELLING AND DISCUSSION

The computer analysis programs were run and critical parameters extracted. (Figure 4).

Blocks have been shown to "settle in" and the block modulus values chosen reflect in each case the lowest values were chosen. This ensured the ultimate choice of block pavement to be conservative, or include a hidden factor or safety. In time and with more experience it will be possible to input higher modulus values to effect savings in layer thickness or reductions in material quality in the design of pavement sections to carry similar loading.

Critical parameters identified in the modelling are often taken in the centre of a layer under consideration and some modification to these values must be made for the upper and lower fibres of the layer, when interpreting results. In the case of the subbase the parameters were calculated at 200 mm below the interface with the overlaying layer.

In the first case modelled (No. 1 on Figure 5) the critical layer is seen to be No. 3. Here the strain value of 117 indicates a short life in the first phase of the cemented material. However rapid breakdown into the equivalent granular state is not a problem with block pavements since reflective cracking is not a problem.

The factor of safety value of 0,37 in the final phase shows that a short life may be indicated - although this might be

100 000 repetitions of an E80 axle before terminal conditions would apply. Terminal conditions of block pavements may be more severe as compared with black top pavements, since surface deformations can be easily reinstated if necessary.

In a similar examination of critical parameters for the other calculations in Figure 5 the block layer is never shown as critical. In most cases the cemented layers show rapid break down into the equivalent granular state during which the main part of the life of the pavement occurs.

The modulus value for the blocks as modelled may be a measure of the resistance of the blocks to flexure which would be low because of the sand jointing. The compressive resistance of blocks is high especially when supported over a granular subbase. Realistic modelling of blocks is therefore a measure of the compressive rather than flexural strength.

Computer run No. 8 (Figure 5) shows the final modelled pavements with more realistic modulus values attained from the initial analysis.

The effect of the bedding sand was found to be negligible and is confirmed by a comparison of the critical parameters output in evaluations 8a and 9a. The bedding sand is a relatively thin layer and if a modulus of 0 were given to it it would serve as a sliplayer which is an unrealistic condition. In the final modelling it was decided to add the thickness of this and to the blocks and compute critical parameters accordingly. A value of 8 000 for the modulus of the blocks was chosen by considering the blocks as being the equivalent of a cemented state of a C2 pavement.

9. CONCLUSIONS

The above analyses suggests the modulus values for blocks may be between 2 000 and 8 000. Both these figures were used but these did not model the pavements effectively to the state measured in the field. A realistic modulus for the block layer may be between 1 000 and 5 000 depending on the state of the joints. More work is needed in this field because of the numerous variabilities and for the present state of the art a modulus range of 400 to 2 000 would suggest a conservative recommendat ion.

REFERENCES

1. MECDEI (1977) Computer Information Centre for Transportation. Stresses and strains in layered pavements under dual wheel load MECDEI. Manual P5, NITRR, Pretoria, CSIR 1977.

2. MECDE3 (1983). Personal communication with the manager of the Computer Information Centre for Transportation at NITRR. CSIR, Pretoria.

3. CHEV4 (1977). Computer Information Centre for Transportation. Stresses and strains in layered systems. (Chev4 1977 Manual P4 NITRR, Pretoria, CSIR 1977)

4. ELSYM5 (1983). Personal communication with Computer Information Centre for Transportation, NITRR, CSIR Pretoria, 1983.

5. FEPAVE (1983). Available from University of Stellenbosch (1983). RSA.

6. MAPS (1983) available at University of Stellenbosch, RSA.

7. PATERSON, W D 0 and MAREE, J H. An interim mechanistic procedure for the structural design of asphalt pavements. Technical Report RP/5/78, Pretoria, NITRR, CSIR, 1978.

8. MAREE et al (1980), MAREE, J H, VAN ZYL, N J W and FREEME, C R. The effective moduli and the stress dependence of pavement materials as measured in some Heavy Vehicle S imulator tests. Transportation Research Board, USA, 1980.

9. CLIFFORD, J M (1984). Structural design of segmental block pavements for Southern Africa. Technical Report RP/9/84, Pretoria, NITRR, CSIR, 1984.

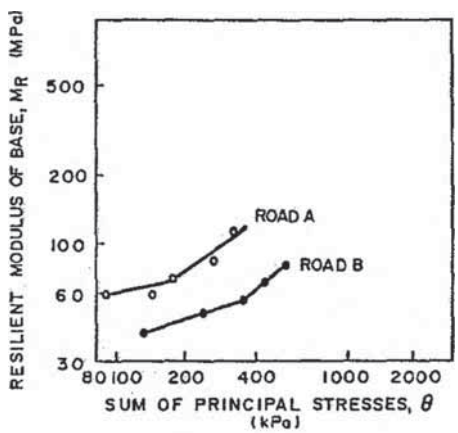
10. CLIFFORD, J M (1984). Some aspects of the structural design of segmental block pavements for Southern Africa. D.Ing Thesis, University of Pretoria, RSA.

MATERIAL CLASSIFICATION	RESILIENT MODULUS(MPa)		POISSONS RATIO	
	POSSIBLE RANGE	MEAN	RANGE	RECOMMEND.
C 2	4000 - 14000			
C 3	3000 - 10000			
C 4	2000 - 7000			
G 2	150 - 800	475	0,1-0,5	0,35
G 4	100 - 600			
G 5	75 - 450			
G 6	50 - 300			
SUBGRADE G7	UNCERTAIN			

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FIGURE I

INPUT VALUES FOR MECHANISTIC MODELLING OF HEAVY INDUSTRIAL PAVEMENTS

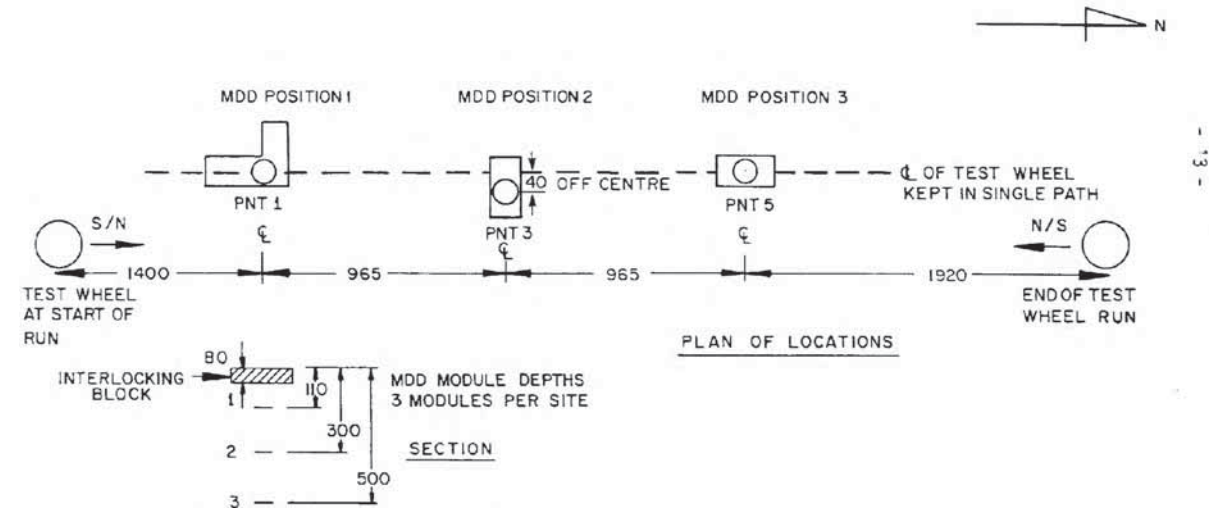


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FIGURE .2

THE STRESS-DEPENDENCE OF A GRANULAR BASE RESILIENT MODULUS AS MEASUREDIN THE HVS TEST

AFTER MAREE ET AL (1990)



940-4-4033/2 NPRL

FIGURE 3

MDD INSTALLATION LAYOUT

PAVEMENT STRUCTURE	ROAD CATEGORY	
60 BLOCKS 20 SAND 150 C2/3 100 G4 SEMI ∞	DESIGN TRAFFIC CLASS	
	PAVEMENT TYPE	BLOCK PAVING (PANEL 23)

INPUT VALUES						CRITICAL PARAMETERS		
LAYER NUMBER	THICKNESS (mm)	POISSON RATIO	E-VALUE (MPa) PHASE 1	PHASE 2	PHASE 3	STRESSES (σ, kPa); STRAINS (ϵ) PHASE 1	PHASE 2	PHASE 3
1	60	0,35	1000	1500	2000	Max. σ_v 520,3		
2	20	0,35	200	200	200	NO CHECKS MADE ON SAND LAYER		
3	150	0,35	6000	2200	350	117$\mu\epsilon$	188$\mu\epsilon$	σ_v = 164,9 (c) σ_v = 27,6 (t)
4	100	0,35	225	225	225	σ_v = 27,6 (c) σ_H = 27,7 (t)	σ_v = 36,2 (c) σ_H = 43,6 (t)	σ_v = 55,2 (c) σ_H = 66,0 (t)
5	SEMI-∞	0,35	50	50	50	ϵ_v = 320$\mu\epsilon$	393$\mu\epsilon$	524$\mu\epsilon$

INTERPRETATION AND EVALUATION					
LAYER NUMBER	LAYER LIFE (E80) PHASE 1	PHASE 2	PHASE 3	STRUCTURE LIFE (E80)	
1			LAYER 3 CRITICAL	0,1 – 0,3 x 10^6	
2			EG4, F.S = 0,37		
3	VERY SHORT		~10^5 (C CLAY)	DEFLECTION (mm) INITIAL	FINAL
4			LAYER 4 –ve FOS.	0,52	0,72
5					

PROFORMA DETAILS OF ELSYM 5 MODELLING

PAVEMENT STRUCTURE	ROAD CATEGORY	
60 BLOCKS 20 SAND 150 C2 100 G4 G6 OR WORSE	DESIGN TRAFFIC CLASS	
	PAVEMENT TYPE	BLOCK PAVING S3d WORST CASE

INPUT VALUES						CRITICAL PARAMETERS		
LAYER NUMBER	THICKNESS (mm)	POISSON RATIO	E-VALUE (MPa) PHASE 1	PHASE 2	PHASE 3	STRESSES (σ, kPa); STRAINS (ϵ) PHASE 1	PHASE 2	PHASE 3
1	60	0,35	1000	1500	2000	APPLIED σ_v = 520		
2	20	0,35	200	200	200	NO CHECKS MADE ON SAND INTERLAYER		
3	150	0,35	8000	2200	350	ϵ_H = 123$\mu\epsilon$	204$\mu\epsilon$	σ_v = 205,0 (c) σ_v = 28,6 (t)
4	100	0,35	225	225	225	σ_v = 54,4 (c) σ_H = 12,3 (t)	σ_v = 71,6 (c) σ_H = 23,7 (t)	σ_v = 90,3 (c) σ_H = 37,9 (t)
5	SEMI-∞	0,35	50	50	50	ϵ_v = 296$\mu\epsilon$	343$\mu\epsilon$	394$\mu\epsilon$

INTERPRETATION AND EVALUATION					
LAYER NUMBER	LAYER LIFE (E80) PHASE 1	PHASE 2	PHASE 3	STRUCTURE LIFE (E80)	
1			LAYER 3 CRITICAL	0,2 – 0,5 x 10^6	
2			EG2, F.S = 0,43		
3	VERY SHORT	—	1,5x10^5 (C)	DEFLECTION (mm) INITIAL	FINAL
4			F.S ~0 LAYER 4	0,40	0,50
5					

PROFORMA DETAILS OF ELSYM 5 MODELLING

FIGURE 4 - TYPICAL DATA

Computer run no.	Pavement structure at sites:	Modulus values				
		Blocks	Bedding sand	1st Sub layer	2nd Sub layer	3rd Sub layer
I	(i)	1000		6000		
		1500		2200		
		2000	200	350	225	50
2	(ii)	1000		8000		
		1500		2400		
		2000	200	450	225	100
3	(iii)	1000		8000		
		1500		2400		
		2000	200	450	225	100
4	(iv)	1500		6000	3500	
		2000		2200	1500	
			200	350	250	50
5	(v)	1000		4000		
		1500		2000	2000	
		2000	200	300	300	50
6	(vi)	1000		4000		
		1500		2000	2000	
		2000	200	300	300	50
7	(vii)	1000		8000	2500	
		1500		2400	1000	
		2000	200	450	200	100
8	(viii)	1000		4000	2500	
		1500		2000	1000	
		2000	200	300	200	100

FIGURE 5 - INPUT DATA FOR ELSYM 5 MODELLING

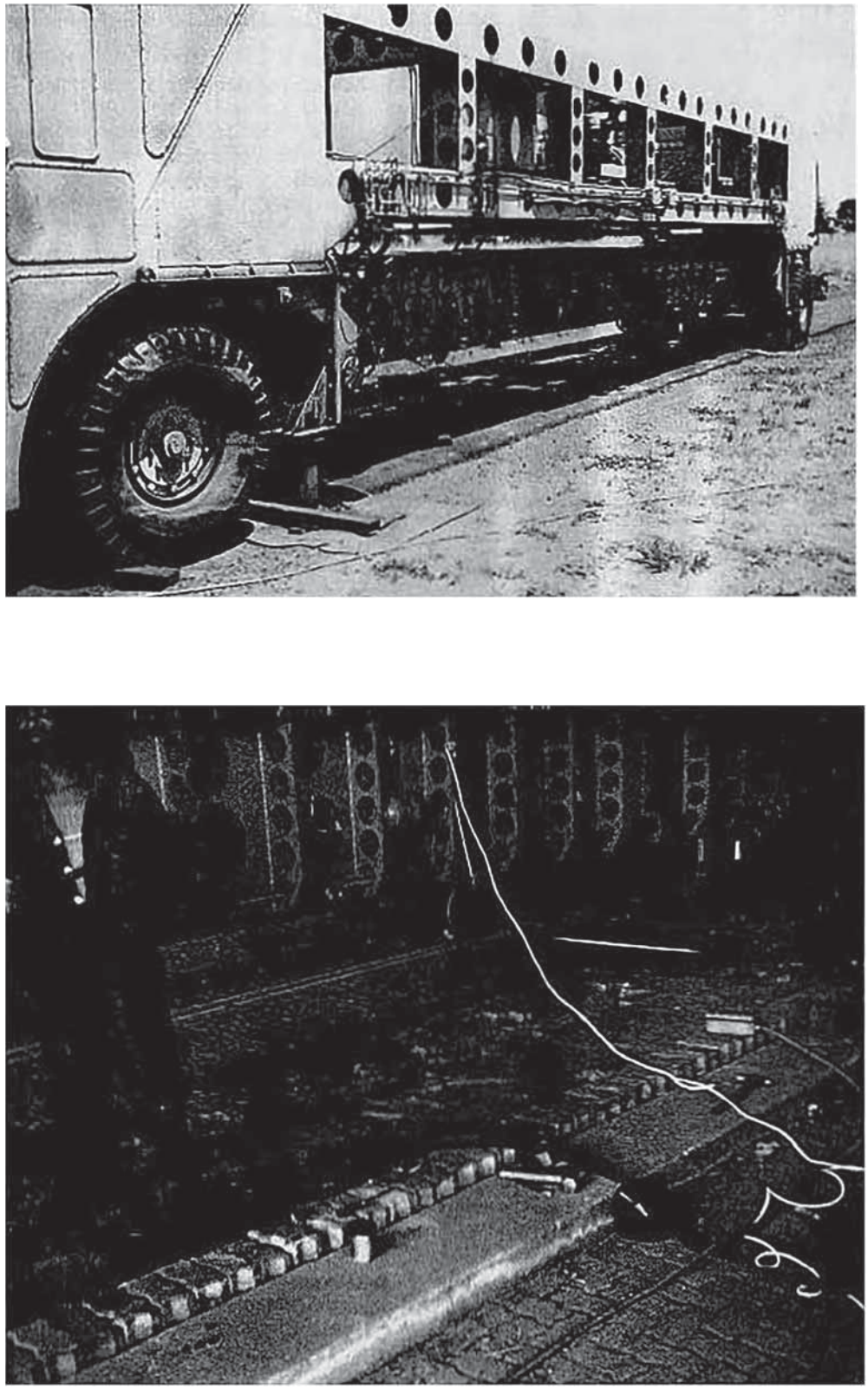


FIGURE 6 - HEAVY VEHICLE SIMULATOR DURING THE TESTS